**Annals of Clinical and Analytical Medicine**
*Original Research*

# Transcranial magnetic stimulation in neurological rehabilitation: A bibliometric mapping of 34 years of literature

TMS in neurorehabilitation: 34 years

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**Abstract**

Aim: This study aims to analyze the global research landscape on transcranial magnetic stimulation (TMS) in neurological rehabilitation using bibliometric methods. It investigates publication trends, key authors and institutions, international collaboration patterns, and disease-specific research distribution to highlight current progress and research gaps.

Material and Methods: A total of 2,245 English-language publications from 1991 to 2025 were retrieved from the Web of Science Core Collection (WoSCC) using a specific search strategy targeting TMS, rehabilitation, and neurological disorders. Bibliometric and scientometric analyses were conducted using Biblioshiny and VOSviewer. Analyses included productivity trends, citation metrics, keyword co-occurrence, thematic clustering, and collaboration networks.

Results: The number of TMS-related publications in neurorehabilitation showed a sharp increase after 2015, with an average annual growth rate of 13.8%. Stroke, spinal cord injury, Parkinson's disease, and multiple sclerosis were the most studied conditions, whereas cerebral palsy, traumatic brain injury (TBI), and ALS remained underrepresented. The most prolific countries were the United States, China, Italy, Canada, and the UK. Institutional and co-authorship networks were primarily centered in North America and Western Europe. Keyword mapping revealed prominent themes, including motor recovery, neuroplasticity, and functional improvement.

Discussion: This is the first bibliometric study to offer a comprehensive overview of TMS in neurological rehabilitation across multiple disease groups. The findings reveal both significant growth in scientific activity and persistent underrepresentation of certain disorders like ALS and cerebral palsy. Future research should prioritize these gaps through multicenter, long-term studies to broaden the clinical application of TMS in neurorehabilitation

**Keywords**

Transcranial Magnetic Stimulation, Neurologic Rehabilitation, Stroke, Bibliometrics, Parkinson Disease

DOI: 10.4328/ACAM.22740 Received: 2025-05-15 Accepted: 2025-06-16 Published Online: 2025-06-26 Printed: 2025-07-01 Ann Clin Anal Med 2025;16(7):516-520
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## Introduction

Transcranial magnetic stimulation (TMS) is a non-invasive, painless, and reliable neuromodulation technique that uses fluctuating magnetic fields to stimulate neural tissues, including the cerebral cortex, spinal roots, and cranial and spinal neurons, while recording the responses via an electromyography (EMG) device [1]. TMS can regulate cortical excitability by delivering magnetic pulses to targeted brain regions, promote neural plasticity, and support the improvement of motor and cognitive functions [2]. Although its exact mechanism of action has not yet been fully elucidated, TMS is suggested to be associated with synaptic plasticity, neurotransmitter regulation, ATP production, and increased vascularization in the application site and even adjacent cortical areas [3].

TMS was first introduced in 1985 and has since been increasingly utilized in both clinical and research settings. Alongside the expansion of its application areas, there has been a significant rise in scientific publications on the topic [4]. The use of TMS modalities, especially as an adjunct therapy in rehabilitation, has gained broader acceptance due to growing levels of supporting evidence [3]. Currently, TMS is clinically applied in the treatment of various neurological disorders, including stroke, amyotrophic lateral sclerosis (ALS), Parkinson's disease (PD), epilepsy, multiple sclerosis (MS), and cerebral palsy (CP) [5].

In individuals with PD, TMS applications have been shown to provide significant improvements in general motor impairment, gait, functional mobility, and balance parameters, with minimal side effects [6]. In stroke patients, moderate to high-quality evidence indicates that TMS contributes to enhanced motor functions and independence during early stages and within the first six months of recovery, thereby facilitating daily living activities [7]. Among individuals with ALS, especially those with cognitive impairment, TMS has been reported to yield short-term positive effects and potentially reduce caregiver burden [8]. In MS, the application of motor TMS in combination with exercise therapy has been reported to reduce both positive symptoms, such as spasticity, and negative symptoms such as fatigue, making it a promising approach for motor rehabilitation [9]. Additionally, another study conducted on MS patients has demonstrated that TMS induces cortical plasticity modulation and consequently improves motor functions [10]. Studies conducted in patients with CP have also confirmed that when TMS is used in conjunction with physical and occupational therapy or constraint-induced movement therapies, it leads to improvements in motor functions and reductions in spasticity [11, 12]. Furthermore, TMS appears to be a well-tolerated intervention for a wide range of symptoms and neurological sequelae following TBI [13]. TMS is also considered a promising non-invasive method for the treatment of spasticity, neuropathic pain, and somatomotor deficits that develop following spinal cord injury [14].

Bibliometric analyses are an important method for identifying publication trends, research foci, influential publications, authors, and institutions in scientific domains [15]. Despite the widespread clinical use of TMS in neurorehabilitation, comprehensive bibliometric studies specifically focused on this area are lacking. The aim of the present study is to analyze the overall trends in the application of TMS within the field of neurorehabilitation, identify research gaps, and draw attention to less-studied subfields. Compared to systematic reviews, bibliometric analysis enables an easier visual representation of publication trends. In this context, the development of TMS in the field of neurorehabilitation will be evaluated through keywords, authors, journals, publications, institutions, and countries.

## Material and Methods

Data regarding the use of TMS in neurorehabilitation were obtained from the Web of Science Core Collection (WoSCC) database on May 8, 2025.

In the search strategy, a combination of keywords related to transcranial magnetic stimulation, rehabilitation, and neurological diseases (e.g., stroke, Parkinson's disease, cerebral palsy) was used. Only publications classified as "article" or "review article" were included in the initial screening. Furthermore, only English-language publications were considered for analysis. A total of 2,245 publications were identified, and all were included in the final analysis.

The reason why the number of disease-specific publications may appear higher than the total number of publications is that a single article may be associated with more than one disease group. Therefore, frequency counts based on disease may exceed the total number of publications. The final dataset was exported in TXT format for further analysis.

### *Data Analysis*

To identify research collaborations, author networks, and core thematic clusters, co-authorship networks and keyword co-occurrence analyses were conducted using the VOSviewer software. VOSviewer provides a robust infrastructure for the visual representation of bibliometric relationships, particularly in the context of network mapping [16]. In addition, the R-based Bibliometrix package was utilized to evaluate the scientific productivity and impact of various research institutions; trends in publication output over the years were also analyzed to reveal the developmental dynamics of the field [17]. Bibliometrix effectively supported the bibliometric analysis process by offering a comprehensive and systematic solution encompassing all stages, including data collection, preprocessing, analysis, and visualization [18].

### *Ethical Approval:*

This study was based on publicly available bibliometric data and did not involve human or animal subjects; therefore, ethical approval was not required.

## Results

In this bibliometric analysis, a total of 2,245 scientific documents published between 1991 and 2025 regarding the use of TMS in neurorehabilitation were evaluated. The average annual growth rate was calculated as 13.8%, with a notable increase particularly after 2015 (Figure 1A). The average document age was 7.68 years, and the average number of citations per document was 3.16. The average annual citation trend peaked in studies published between 1999 and 2003, whereas publications from 2023 onward have, as expected, received fewer citations to date.

Among the publishing institutions, the University of Toronto (n=166), the University of Louisville (n=133), and the University of Minnesota (n=131) stood out. The most productive authors included Edgerton VR (n=27), Liu Y (n=23), Kirton A (n=22), and Fregni F (n=21), indicating a publication network predominantly centered in North America (Figure 1B).

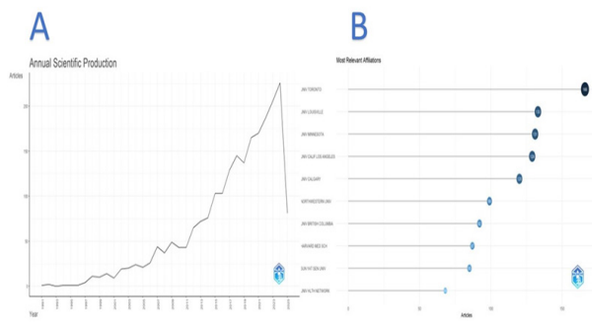


**Figure 1.** A. Publication output by year, generated using the Biblioshiny software 1. B. Most productive authors, generated using the Biblioshiny software

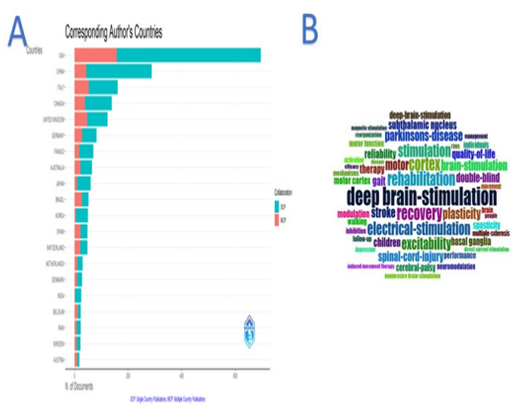


**Figure 2.** A. Most productive countries, generated using the Biblioshiny software 2.B. Word cloud visualization generated using the Biblioshiny software

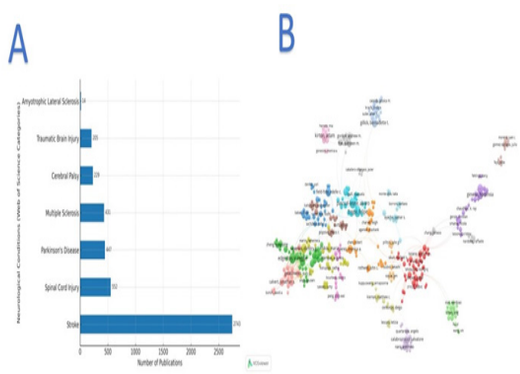


**Figure 3.** A. Number of publications related to TMS by neurological disorder 3. B. Co-authorship network visualization generated using VOSviewer

At the international level, the United States, China, Italy, Canada, and the United Kingdom were the countries with the highest number of publications (Figure 2A). Moreover, the United States was positioned at the center of the collaboration network, both in terms of publication volume and its strong partnerships with numerous countries.

In the keyword analysis, the most frequently encountered terms included "transcranial magnetic stimulation" (n=429), "deep brain stimulation" (n=244), "recovery" (n=191), and "rehabilitation" (n=184) (Figure 2B). These concepts were frequently studied in conjunction with themes such as neuroplasticity, motor cortex, spasticity, and functional improvement (Figure 2B).

The bibliometric analysis of the applications of TMS in neurological rehabilitation reveals notable differences in research intensity among various neurological disorders. According to the search conducted in the Web of Science database, stroke appears as the most frequently studied condition. With a total of 2,743 publications, stroke constitutes the most extensively investigated disease group concerning the rehabilitative use of TMS. This can be attributed to the widespread and promising use of TMS in addressing motor and cognitive impairments that develop following stroke.

Following stroke, the other most frequently studied disease groups include spinal cord injury (552 publications), PD (447 publications), and MS (431 publications). These are chronic neurological disorders characterized by motor and cognitive dysfunction, representing important areas of research for TMS in terms of symptom control and functional improvement.

Groups with fewer publications, such as CP (229 publications) and TBI (205 publications), demonstrate the potential of TMS applications in pediatric rehabilitation and acquired brain injury, respectively. Although these areas remain underexplored, they offer significant opportunities for future research.

On the other hand, ALS is represented by only 14 publications, making it the least studied group among the conditions included in this analysis. The rapid progression of ALS, its heterogeneous clinical course, and uncertainties in treatment response are considered limiting factors for TMS-related research in this population (Figure 3A).

These findings indicate that TMS is widely addressed in the context of motor and cognitive rehabilitation processes. The keyword co-occurrence network also reflects these clinical themes and their associated concepts in detail. Concept mapping analyses reveal dense conceptual clusters formed around key themes such as PD, spinal cord injury, rehabilitation, and the subthalamic nucleus. These themes are examined in conjunction with functional recovery, motor improvement, brain plasticity, and technological applications (e.g., brain-machine interface).

According to the citation analysis, the journals with the highest number of citations were Movement Disorders (n=4,370), Neurology (n=4,163), and Brain (n=3,952). The highly cited studies published in these journals indicate that the role of TMS in motor dysfunction and neurodegenerative diseases has been extensively investigated. Among the journals publishing the greatest number of articles, Neuromodulation (n=78), Frontiers in Neurology (n=72), and IEEE Transactions on Neural Systems

and Rehabilitation (n=55) were the most prominent.

The international collaboration map generated using VOSviewer visualizes country-based scientific interactions. Türkiye holds a moderate position through its connections with countries such as Spain, Germany, and France. In the institutional collaboration map (Figure 3B), institutions such as Northwestern University, UCLA, the University of Toronto, and the University of Oxford were found to have high network connectivity. In terms of the author collaboration network (Figure 3B), clusters were observed around researchers such as Edgerton, Fregni, Pascual-Leone, and Field-Fote.

The analyses of collaboration at both the institutional and authorship levels (Figure 3B) indicate that scientific output in the field of TMS is largely clustered around institutions based in North America (particularly the United States and Canada) and Western Europe (the United Kingdom, Germany, and Italy). The central positioning of institutions like Northwestern University, UCLA, the University of Toronto, and the University of Oxford within the network highlights their key roles not only in productivity but also in collaborative influence. Similarly, the co-authorship network reflects international connections through clusters shaped around authors such as Fregni, Edgerton, and Pascual-Leone.

Although Turkiye is present within these networks, it is primarily represented through secondary connections and demonstrates a mid-level regional interaction profile. This suggests that while Turkiye contributes to the TMS-related neurorehabilitation literature, it does not yet occupy a central leadership role at the global level. Therefore, it is important for researchers to establish stronger institutional collaborations to enhance international visibility and contribute more significantly to the advancement of the field.

## Discussion

This bibliometric analysis reveals a significant growth and evolution in the literature on the use of TMS in neurorehabilitation between 1991 and 2025. When examining publication trends by year, a notable acceleration is observed beginning in the mid-2000s. While TMS-related studies were almost nonexistent in the early 1990s, a slow upward trend began in the 2000s and gained marked momentum from the 2010s onward. Indeed, Zheng et al. [19] reported that the number of annual publications increased from approximately 200 in 2009 to 375 in 2018, indicating a steady and positive trend in publication growth during that period. Similarly, Juhi et al. [20], emphasized that stroke rehabilitation-focused studies remained limited until 2011, but experienced a sharp increase after 2014, reaching record levels between 2022 and 2024.

Our analysis confirms that over a broad time span, interest in TMS within the field of neurorehabilitation has grown exponentially, with annual publication numbers peaking in the 2020s compared to previous decades. This upward trend likely stems from increasing recognition of TMS's therapeutic potential.

Analyses focusing on stroke rehabilitation have shown that the left dorsolateral prefrontal cortex and the primary motor cortex are among the most frequently targeted regions; low-frequency TMS has been associated with inhibition, while high-frequency TMS has been linked to excitation. Juhi et al. [20] noted that the most highly cited studies in this area are generally controlled trials that support improvements in motor function. Similarly, our analysis also demonstrated that publications related to stroke are high in number and have gained increasing momentum over the years.

In a bibliometric analysis specifically focused on PD, it was reported that, in recent years, there has been an increase in studies investigating the effects of TMS on both motor and non-motor symptoms [20]. The same study emphasized that protocols targeting the primary motor cortex and dorsolateral prefrontal cortex were particularly prominent, and that high-frequency TMS could produce significant effects on gait and motor scores. In our study, the volume of publications related to PD and the increasing trend in this area are consistent with the existing literature.

In the broader analysis conducted by Zheng et al. [21], publications in the field of TMS demonstrated a consistent annual increase between 2009 and 2018, with a particular concentration in developed countries such as the United States, Canada, and Germany. In our analysis, while these countries remained prominent, a noticeable rise in the number of publications from China and South Korea has also been observed in recent years, suggesting that these countries may be considered emerging contributors in terms of research output. This finding aligns with the study by Juhi et al., which identified China as the country with the highest number of publications in the stroke-TMS literature.

The decrease observed in the average number of citations after 2020 may largely be due to the fact that studies published during these years have not yet had sufficient time to accumulate citations. Citation delays are typical in recent publications. Therefore, the relatively low citation counts of articles published in or after 2020 reflect a natural delay effect that may be compensated over time. This situation stems from the time-dependent nature of bibliometric analyses, and the long-term impact of recent studies will become clearer in the future.

Most previous bibliometric analyses have focused on specific neurological conditions such as stroke or PD. This study provides one of the first thematic analyses across multiple neurological conditions involving TMS. In this respect, it is a pioneering study that offers a holistic assessment of TMS's role in neurological rehabilitation. While the literature includes separate bibliometric studies addressing either clinical or disease-specific aspects of TMS in neurorehabilitation, the uniqueness of our study lies in its integration of both dimensions into a unified, comprehensive evaluation.

### *Limitation*

Our study has several limitations. It includes only publications indexed in the WoSCC database; other data sources such as Scopus, PubMed, and Embase were excluded from the analysis. Bibliometric analyses rely on quantitative metrics and do not assess qualitative aspects such as methodological rigor, clinical efficacy, or outcome validity. Only English-language publications were included in the analysis, which may have excluded important studies published in other languages. Articles published after 2023 may not yet have had enough

time to accumulate citations. Keyword and thematic analyses are based on automated indexing systems defined by journal databases, which may lead to limited representation of term diversity and semantic overlap. Clinical effectiveness, patient response, or functional outcomes of TMS applications were not directly addressed within the scope of this analysis.

## *Conclusion*

This bibliometric analysis has revealed the scientific development of TMS in the field of neurorehabilitation in a multidimensional manner. It is important that future studies evaluate the effects of TMS in underrepresented clinical areas indicated by bibliometric findings with multicenter and long-term designs.

***Scientific Responsibility Statement***

*The authors declare that they are responsible for the article's scientific content including study design, data collection, analysis and interpretation, writing, some of the main line, or all of the preparation and scientific review of the contents and approval of the final version of the article.*

***Animal and Human Rights Statement***

*All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or compareable ethical standards.*

***Funding:*** *None*

***Conflict of Interest***

*The authors declare that there is no conflict of interest.*

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***How to cite this article:***
***Lütfiye Parlak, Transcranial Magnetic Stimulation in Neurological Rehabilitation: A Bibliometric Mapping of 34 Years of Literature.*** *Ann Clin Anal Med 2025;16(7):516-520*